

Master's Thesis

Vulnerabilities in Privacy-Preserving Record Linkage: The Threat of Dataset Extension Attacks

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by

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Abstract

The abstract should serve as an independent piece of information on your Thesis conveying a concise description of the main aspects and most important results. It should not be excessively long.

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Acronyms

AI Artificial Intelligence

ANN Artificial Neural Network

BF Bloom Filter

DEA Dataset Extension Attack

ELD Encoded Linkage Data

GMA Graph Matching Attack

ML Machine Learning

PII Personally Identifiable Information

PPRL Privacy-Preserving Record Linkage

PRNG Pseudo-Random Number Generator

SMC Secure Multi-Party Computation

TMH Tabulation MinHash Encoding

TSH Two-Step Hash Encoding

1. Introduction

Linking data and records is an important component of research, software development and software projects. The primary reason for integrating data from different sources is to gain richer, more comprehensive insights about the same entity. Initially, deterministic record linkage, which relies on exact matches between predefined identifiers such as unique IDs, was the main method used in early linkage techniques. However, deterministic approaches often fail in real-world scenarios where data may suffer from inconsistent formatting, typographical errors or missing values, making exact matches impossible [HSW07].

The introduction of a probabilistic framework for record linkage by Fellegi et al. in 1969 [FS69] marked a significant advance in overcoming these limitations. Their work, “A Theory for Record Linkage” [FS69], proposed a statistical method for linking records across datasets by calculating the probability that two records refer to the same entity, even when there are inconsistencies in the data. Their approach evaluates common attributes and assigns weights based on the likelihood of a match as opposed to a random similarity. By accounting for discrepancies in real-world data, the so-called Fellegi-Sunter model has become a fundamental methodology for data linkage, particularly in heterogeneous and distributed data environments where traditional deterministic methods fall short.

Such a probabilistic approach to record linkage is important in sectors such as healthcare and social sciences, where data is often distributed across multiple institutions or sources and lacks unique identifiers. In these fields, the ability to integrate datasets is essential for gaining insights and improving outcomes. In the United States, for example, the healthcare system is highly fragmented, consisting of numerous independent entities such as hospitals, clinics, insurance companies, public health agencies, and research institutions. Each of these organisations collects and stores patient data independently, often using different systems and, more importantly, different formats. This fragmentation creates significant challenges when trying to track patient outcomes, monitor disease outbreaks, or evaluate the effectiveness of treatments across populations. Effective data linkage can bridge these gaps by linking records that refer to the same individual across multiple datasets. This integration is critical for tasks such as epidemiological research, public health surveillance, personalised medicine and healthcare quality improvement [PSZ+24; VSCR17].

For example, during the COVID-19 pandemic, the inability to efficiently link data between testing centres, hospitals and vaccination sites limited timely tracking of infection rates and vaccination outcomes. Had more robust data linkage mechanisms been in place, public health officials could have responded more effectively to outbreaks and targeted interventions to specific populations. Data linkage thus plays a critical role in transforming fragmented data landscapes into unified and actionable insights, leading to more informed decision-making. In response to the COVID-19 pandemic, organisations such as the Centers for Disease Control and Prevention and the Food and Drug Administration have launched projects to address these challenges and further develop linkage techniques [PSZ+24].

In scenarios such as the COVID-19 pandemic, data integration efforts often involve linking records on natural persons from multiple sources. For example, integrating data from differ-

ent healthcare providers, laboratories and public health agencies typically requires the use of pseudo-identifiers derived from Personally Identifiable Information (PII), such as names, dates of birth or other sensitive information. However, reliance on PII for linkage raises significant privacy concerns, as improper handling of such data can lead to re-identification of individuals, with potentially serious consequences such as data breaches, identity theft or unauthorised access to personal health information [PSZ+24; SBR09].

The increasing digitisation of personal data has already led to large-scale data breaches, demonstrating the risks of improperly secured data. Notable incidents such as the Cambridge Analytica scandal, in which personal data was misused for political profiling, highlight the ethical and regulatory challenges of data integration [IH18]. Similarly, healthcare data leaks have raised concerns about the implications of unauthorised access to medical histories, genetic data and insurance records. Leaks of personal health information can have serious consequences, including blackmail, discrimination, and fraud, which can cause significant personal harm. For example, individuals whose medical histories are exposed may face discrimination in employment or insurance, while others may become targets of scams that exploit their health conditions. The potential for such abuse underlines the critical importance of robust data protection measures by working with PII [Smi16].

To address these privacy risks, various techniques have been developed to protect PII during the linking process, primarily by encrypting the data prior to linking. However, the use of encrypted PII as pseudo-identifiers presents additional challenges. The key question is how to efficiently encrypt sensitive information while maintaining the ability to accurately match records [SBR09].

Therefore, Privacy-Preserving Record Linkage (PPRL) techniques are designed to facilitate data integration without exposing sensitive information, ensuring that datasets can be securely linked across different entities. To enable linkage while preserving privacy, similarity preserving encryption is applied to the PII. Without such similarity preserving encryption, matches between encrypted entities in different databases would not be possible [SBR09; VSCR17].

Over time, three main privacy-preserving encryption schemes have emerged as enablers for PPRL [SAH24; VCRS20].

Bloom Filter (BF) encoding is the most widely used technique in PPRL and is often considered the reference standard [SAH24]. Originally introduced by Burton Bloom in 1970 as a probabilistic data structure for efficient set membership testing [Blo70], BFs were later adapted for PPRL due to their simplicity and efficiency in both storing and computing set similarities. Their compact representation and probabilistic nature make them ideal for scalable PPRL systems, especially in environments dealing with large datasets [SBR09]. The seminal work of Schnell et al. demonstrated the use of BFs in PPRL, particularly in healthcare, highlighting their ability to perform secure record matching without exposing sensitive identifiers [SBR09]. However, BFs are not without limitations. Their vulnerability to graph-based attacks and pattern exploitation has driven research into improving their security. Techniques such as diffusion have been proposed to obscure recognisable patterns and increase security [AHS23; SAH24]. For example, Armknecht et al. [AHS23] explored methods to strengthen the security of BF by adding a linear diffusion layer to the BF-based PPRL approach, which complicates pattern mining attacks.

To address some of these weaknesses of BFs, Tabulation MinHash Encoding (TMH) has been introduced as a more secure alternative. MinHash, first developed by Broder in 1997 for estimating set similarities in large document collections [Bro97], has been adapted using tabulation-based hashing [Smi17]. Although less widely used than BFs, TMH offers distinct

advantages, including stronger security guarantees against re-identification attacks. However, these benefits come at the cost of increased computational complexity and memory usage, which may limit its applicability in resource-constrained environments [Smi17].

A further development in encryption techniques is the introduction of Two-Step Hash Encoding (TSH), which aims to combine the strengths of both BFs and TMH while mitigating their respective weaknesses. As detailed by [RCS20], TSH employs a two-stage process: data is first encrypted using multiple BFs, followed by an additional hashing layer that transforms the encrypted data into a set of integers suitable for similarity comparison. This layered approach enhances privacy by adding an extra layer of obfuscation, making it more resistant to attack, while maintaining efficient similarity computations [RCS20; VCRS20].

In practice, BF-based PPRL has become the dominant standard and is widely used in areas such as crime detection, fraud prevention and national security due to its balance of efficiency and ease of implementation. However, BF-based PPRL systems are not without limitations and vulnerabilities. Previous research has shown that there are several attacks targeting PPRL systems, with a focus on exploiting the weaknesses inherent in BF encodings. These attacks specifically target weaknesses in BF constructions, such as the weaknesses introduced by double hashing, structural flaws in filter design, and susceptibility to common pattern-mining techniques. Notably, no specific attacks have been developed for TMH or TSH encodings, suggesting that research has focused primarily on the more widely used BF scheme. [VCRS20]

However, a more recent and practical attack has emerged that exploits vulnerabilities common to all PPRL encryption schemes. The Graph Matching Attack (GMA) uses publicly available data, such as telephone directories, to re-identify encrypted individuals based on overlapping records between plaintext and encrypted databases [SAH24; VCRS20]. Unlike previous attacks that focus solely on the encryption scheme of BFs, the GMA works independently of the encryption scheme chosen. It therefore exploits the graph structure of encoded datasets to re-identify records. Given two datasets - a plaintext reference dataset and an encrypted dataset - an attacker can construct similarity graphs where nodes represent individuals and edges represent similarity scores. By solving a graph isomorphism problem, attackers can infer one-to-one mappings between encrypted and plaintext records, effectively breaking the privacy guarantees of PPRL. The effectiveness of GMAs depends on the overlap between the two sets of data; the greater the overlap, the higher the probability of successful re-identification. While GMAs can successfully re-identify individuals present in both the plaintext and encrypted datasets, their effectiveness is limited to the overlapping subset of the two databases [SAH24; VCRS20].

This work aims to go beyond traditional GMAs by re-identifying not only individuals present in the overlapping datasets, but as many individuals as possible from the encrypted PPRL data. To achieve this, the newly introduced Dataset Extension Attack (DEA) builds on the foundations laid by GMAs. The DEA uses an Artificial Neural Network (ANN) trained on the subset of previously re-identified individuals to predict and decode the remaining encrypted records. In doing so, the DEA significantly expands the scope and effectiveness of the attack, enabling broader de-anonymisation of PPRL datasets beyond the limitations of existing graph-based methods.

1.1. Motivation

The increasing use of PPRL in highly sensitive areas such as healthcare, finance and national security requires research to validate existing techniques and ensure robust privacy [SBR09]. As data-driven applications continue to evolve, the complexity and volume of data being collected and linked across multiple sources is growing rapidly. While PPRL systems are designed to facilitate secure data integration without compromising privacy, evolving cybersecurity threats and attack techniques highlight the urgent need to reassess the resilience of these systems [VSCR17].

Privacy has always been a critical concern in data management, but its importance has been intensified in the era of Artificial Intelligence (AI) and Machine Learning (ML). These technologies increasingly rely on large data sets, often containing sensitive PII such as medical records, financial transactions or behavioural data for training. If compromised, the exposure of such data can lead to serious privacy violations, including identity theft, financial fraud and discrimination. The rise of data brokerage, where personal information is collected, aggregated and sold - often without explicit user consent - further exacerbates privacy concerns. This commoditisation of personal data has made PII an attractive target for malicious actors, increasing the risk of unauthorised data linking and re-identification attacks. As AI models become more advanced, the demand for rich, high-quality data continues to grow, making privacy an increasingly pressing issue [KM24; MK19].

In this context, the vulnerability of PPRL systems to emerging attack methods is of particular concern. While PPRL techniques such as BF are designed to hide sensitive identifiers during the data linkage process, recent research has shown that these systems are vulnerable to GMAs. GMAs exploit the similarity preserving properties of common encryption schemes to re-identify individuals by comparing patterns in encrypted records with those in publicly available plaintext records. This approach undermines the fundamental goal of PPRL: to protect sensitive data during the record linkage process. Although current GMAs are limited to re-identifying individuals present in both the encrypted and plaintext datasets, even partial data exposure in highly sensitive areas can have serious consequences [SAH24; VCRS20].

The introduction of DEAs poses an even greater threat to the integrity of PPRL systems. Unlike GMAs, DEAs aim to extend the scope of re-identification to as many individuals as possible within the encrypted database. Using ANNs trained on previously decoded data from GMAs, DEAs can predict and decode additional records, potentially leading to the complete de-anonymisation of entire encrypted datasets. This represents a paradigm shift, as it challenges the viability of widely used PPRL techniques, such as BF-based encryption, which have been considered secure.

The primary motivation for this research is to proactively investigate and demonstrate the consequences of such advanced attacks in order to prevent their realisation in real-world scenarios. By exposing the potential vulnerabilities of PPRL systems, this work aims to demonstrate how attackers could exploit decrypted data to compromise privacy on a large scale. A successful implementation of the DEA will provide empirical evidence that state-of-the-art methods are insufficiently secure, highlighting the urgent need for more robust privacy-preserving techniques.

Furthermore, there is a notable gap in current research regarding the extension of attack capabilities beyond the intersection of datasets. While significant efforts have been made to address the vulnerabilities exposed by GMAs, there is a lack of comprehensive studies exploring how ML can be used to generalise these attacks and compromise entire databases. This research

aims to fill this gap by developing and evaluating the **DEA**, thereby contributing to a broader understanding of **PPRL** vulnerabilities.

By addressing this gap, this thesis aims to contribute to the body of knowledge on **PPRL** vulnerabilities and serve as a foundation for future research aimed at strengthening these systems. The knowledge gained from this study will not only enable the development of more secure **PPRL** techniques, but will also influence best practices in privacy and security.

1.2. Related Work

The study by Vidanage et al. [VCRS20] represents a significant advance in the field of **PPRL** through the introduction of a new attack method known as **GMA**. Their work begins with a comprehensive overview of **PPRL** systems and the similarity preserving encryption techniques commonly used, such as **BFs**. The **GMA** exploits weaknesses in these encoding schemes by exploiting their ability to preserve partial similarity information even after encryption. By constructing similarity graphs from both encrypted and plaintext datasets, the **GMA** solves a graph isomorphism problem to align nodes and successfully re-identify individuals in the encrypted dataset using publicly available sources such as telephone directories. This method demonstrates the universal applicability of **GMA**s across different **PPRL** schemes, and highlights a critical weakness in systems previously thought to be more robust [VCRS20].

Building on this foundation, Schäfer et al. [SAH24] revisited and extended the work of Vidanage et al. Their contribution lies in a meticulous reproduction and replication of the original **GMA**, during which they identified a critical flaw: an undocumented pre-processing step in the provided codebase that inadvertently increased the effectiveness of the attack. While this step was originally intended to improve computational performance, it introduced errors into the proposed **GMA**. Schäfer et al. corrected this problem and further optimised the **GMA**, resulting in improved robustness and efficiency. Their improved implementation achieved higher re-identification rates compared to the original approach. This improvement not only validates the vulnerabilities highlighted by the **GMA**, but also highlights the potential for refining attack methodologies to expose even greater weaknesses in **PPRL** systems.

The work of Schäfer et al. is particularly relevant to this thesis, as their improved **GMA** implementation and accompanying codebase form the basis of the **DEA** proposed in this study. While the **GMA** is limited to re-identifying individuals present in both encrypted and plaintext datasets, the **DEA** seeks to extend the scope of re-identification beyond this intersection. Using **ANNs** trained on the re-identified individuals from the **GMA**, the **DEA** aims to predict and decode additional datasets, potentially leading to complete de-anonymisation of encrypted datasets.

To date, no existing research has proposed an approach comparable to the **DEA**. This thesis addresses this gap by developing and evaluating the **DEA**, thereby contributing to a broader understanding of **PPRL** vulnerabilities and highlighting the urgent need for more secure data linking techniques.

1.3. Contribution

The contribution of this thesis is divided into three main parts. First, a comprehensive analysis of **PPRL** systems is carried out, with particular emphasis on the three main encoding schemes: **BF** encoding, **TSH** encoding and **TMH** encoding. This analysis aims to highlight the

basic principles, strengths and weaknesses of each encryption scheme, setting the stage for the subsequent investigation of their susceptibility to [DEA](#).

Next, the current state of the art [GMA](#) is analysed and its limitations are discussed in detail. Although [GMAs](#) have proven effective in re-identifying individuals within overlapping datasets, their applicability is limited to the intersection of plaintext and encrypted records. This inherent limitation highlights the need for more advanced attack strategies that can go beyond this.

The main focus of this thesis is the implementation and evaluation of the [DEA](#), which attempts to outperform the capabilities of [GMAs](#) by decrypting a larger fraction of encrypted records. To achieve this, the thesis examines the conceptual foundations, theoretical underpinnings and technical requirements of the [DEA](#). Building on the initial re-identifications made by the [GMA](#), the [DEA](#) employs a supervised machine learning approach, specifically using [ANNs](#) trained on previously decoded data to predict and re-identify remaining encrypted records. This method significantly extends the scope of de-anonymisation in [PPRL](#) systems and provides a novel approach to current research.

The [DEA](#) is then evaluated against the three main [PPRL](#) encoding schemes. While the specific encoding scheme has minimal impact on the [GMA](#), which is primarily based on solving a graph isomorphism problem, it plays a role in the [DEA](#). This is due to the fact that the [ANN](#) has to be trained separately for each encoding scheme to account for the unique structural features and nuances of the encoding. However, the [DEA](#) is designed with adaptability in mind, ensuring that it can be effectively applied across different encoding schemes, thus increasing its generalisability and practical relevance.

Through this research, the thesis aims to answer critical questions about the robustness of [PPRL](#) systems. It investigates how effective supervised machine learning-based [DEAs](#) are at re-identifying the remaining entries that [GMAs](#) cannot decode. It also examines how different encoding schemes affect the performance and accuracy of the [DEA](#), providing insight into which schemes are more susceptible to such attacks and why. By addressing these issues, the thesis contributes to a deeper understanding of the vulnerabilities inherent in [PPRL](#) systems and lays the groundwork for the development of more secure privacy preserving techniques.

1.4. Organization of this Thesis

This thesis is divided into four main sections: technical background, methodology, results, and conclusion.

First, an overview of [PPRL](#) systems is given, with particular emphasis on a thorough analysis of the most commonly used encoding techniques. Next, the existing [GMA](#) is introduced and explained in order to provide the basis for the study. In addition, an overview of [ANNs](#) is given to provide the necessary background knowledge.

Next, a detailed description of the attack model for the [DEA](#) is outlined, including how [ANNs](#) are used to enhance the attack. This is followed by an explanation of the actual implementation of the [DEA](#), along with a discussion of the experiments conducted. The results of the [DEA](#) on different encryption schemes are then analysed and evaluated. Finally, the thesis concludes with a summary of the main contributions, a discussion of the broader implications, and suggestions for future research.

2. Background

This chapter provides an overview of the key concepts relevant to this thesis, including PPRL, various encoding techniques used in secure linkage and attacks. PPRL enables different organizations to link records belonging to the same individual across datasets while preserving privacy, making it a crucial tool. However, the security of such methods heavily depends on the encoding techniques employed to transform sensitive data into a more privacy-preserving format [VCRS20].

To understand the vulnerabilities of PPRL systems, we examine three key encoding techniques: BF, TMH, and TSH, each offering different trade-offs between efficiency, privacy, and robustness against attacks. While these methods aim to prevent direct access to plaintext identifiers, they remain susceptible to adversarial techniques designed to infer or reconstruct the original data [SAH24; VCRS20].

One such adversarial approach is the GMA, which leverages structural similarities between encoded and non-encoded datasets to re-identify individuals. Although GMAs are powerful in reconstructing intersections of datasets, they are limited to the intersection of the two datasets. To extend GMAs beyond known intersections, we explore ANN, which can learn complex patterns in encoded data and increase identification rates [SAH24; VCRS20].

By integrating these concepts, this chapter establishes the necessary foundation for understanding the DEA introduced later in this thesis, demonstrating how machine learning techniques can be employed to bypass existing privacy-preserving mechanisms.

2.1. Overview of PPRL

PPRL enables the linkage of records from different databases that refer to the same individual while preserving privacy. Traditional record linkage relies on unique identifiers, but these are often unavailable or inconsistent due to variations in formatting, spelling, or missing data across different databases. Linking records directly on plaintext data poses significant privacy risks. To mitigate these risks and prevent further threats to data security, regulations such as the European Union’s General Data Protection Regulation have been established to govern the handling of PII [SAH24; VCRS20].

To enable record linkage using PII while preserving privacy, PPRL employs similarity-preserving encoding on quasi-identifiers, allowing linkage to be performed on encoded representations rather than raw data. This approach protects identities while still facilitating record matching based on encoded similarities and probabilistic approaches [SAH24; VCRS20].

The security of PPRL schemes depends on the encoding techniques used. Broadly, PPRL methods fall into two categories: perturbation based techniques and Secure Multi-Party Computation (SMC) based techniques. SMC-based techniques provide strong security guarantees and high accuracy but suffer from computational and communication overheads. Conversely, perturbation-based techniques balance linkage quality, scalability, and privacy protection, making them more practical for real-world applications [VCRS20].

A typical PPRL system involves three main parties working together to enable the linkage while maintaining privacy. The data owners, who are responsible for maintaining their respective databases, D and D' , encode the quasi-identifiers by agreeing on an encoding scheme with the corresponding parameters before sharing them with the linkage unit. The linkage unit, a trusted entity, performs the actual record linkage using only the encoded representations, without access to the original identifiers. Once the linkage is completed, the linkage unit assigns unique pseudonyms to the successfully linked records and returns the pseudonymized dataset to the data owners. The data owners then replace the linkage data with these pseudonyms before sending the dataset to the data analysts. The analysts can merge the records based on these identifiers and proceed with further research and analysis, all while minimizing the risk of re-identification and protecting individual privacy [SAH24].

Each database record can therefore during the linkage process be represented as $r = (\lambda, \sigma)$, where λ denotes the linkage data which are encoded quasi-identifiers such as names and birth-dates and σ refers to the remaining microdata like in a health care scenario patient information [SAH24].

Linkage in PPRL is performed probabilistically, meaning that two records, r and r' , are considered linked if their similarity score on $\text{sim}(\lambda_r, \lambda_{r'})$ exceeds a predefined threshold. The choice of threshold plays a crucial role in balancing the quality of the linkage. Lower thresholds tolerate more variation and matches between records but increase the likelihood of false positives, while higher thresholds reduce false positives but may miss legitimate matches. Thus, selecting the optimal threshold is a trade-off that requires careful consideration of the specific goals and constraints of the linkage process [SAH24].

A robust PPRL scheme must satisfy several important criteria to ensure effective and secure linkage. First, a similarity function, $\text{sim}(\lambda_r, \lambda_{r'})$, must exist to determine if two records belong to the same entity based on a predefined threshold. Second, an encoding scheme must be applied to λ in such a way that the linkage unit cannot reconstruct the original data. Finally, a function $\text{sim}(\text{enc}(\lambda_r), \text{enc}(\lambda_{r'}))$ must be available that allows similarity computations on encoded data which preserved similarity properties. These requirements ensure both the privacy and the effectiveness of the record linkage process [SAH24].

One common approach for measuring similarity for two quasi identifiers is using n-grams. Here, string values are divided into overlapping substrings of length n using a sliding window approach [SAH24]. For example, for the string “hello” with $n = 2$, the n-grams are:

$$\{\text{he}, \text{el}, \text{ll}, \text{lo}\}$$

The similarity of two sets of n-grams can then be computed using metrics such as the Dice Coefficient [SAH24]

$$\text{Dice}(X, Y) = \frac{2 \times |X \cap Y|}{|X| + |Y|}$$

or using the Jaccard Similarity [SAH24]

$$\text{Jaccard}(X, Y) = \frac{|X \cap Y|}{|X \cup Y|}$$

PPRL has been successfully applied in various domains, demonstrating its practical importance in securely linking records across institutions while preserving privacy. Notable applications include the Social Investment Data Resources (SIDR), the Lumos Initiative, the Swiss

National Cohort, and the Gemeinsamer Bundesausschuss (GBA). These implementations highlight the versatility of PPRL in diverse contexts, where privacy protection is essential while enabling effective data linkage for research and analysis [SAH24].

2.2. Key Encoding Techniques

In the context of PPRL, three primary encoding techniques have emerged BF, TMH and TSH. These encoding methods are essential for transforming sets of quasi-identifiers into fixed-length representations that preserve similarity information while maintaining privacy [SAH24; SBR09; VCRS20].

PPRL typically involves encoding sets of quasi-identifiers before linkage. A set in this context is generally a collection of n-grams, which are substrings of length n extracted from one or multiple attributes using a sliding window approach. Since input data varies in length, all encoding techniques in PPRL must take arbitrarily long inputs (sets of n-grams) and produce fixed-length encoded outputs. This ensures that similarity computations can be efficiently performed on encoded data by the linkage unit without accessing the raw identifiers [SAH24; VCRS20].

Before linkage, data owners must agree on the encoding scheme and share necessary cryptographic secrets to facilitate secure comparison. Among the available techniques, BFs are the most widely used approach for record linkage [SAH24].

2.2.1. BFs

BFs were originally developed for efficient membership testing in set structures without requiring direct access to the sets themselves [Blo70]. Due to their ability to efficiently compute set similarities in a privacy-preserving manner, they have been widely adopted in PPRL applications [SAH24; SBR09; VCRS20].

A BF $b \in \{0, 1\}^l$ is a bit vector of length l . It uses $k \geq 1$ independent hash functions $H = \{h_1, h_2, \dots, h_k\}$, where each function maps an arbitrary input to a position in the filter [SAH24; SBR09]:

$$h_i : \{0, 1\}^* \rightarrow \{1, \dots, l\}, \quad \forall i \in \{1, \dots, k\} \quad (2.1)$$

Initially, the BF is set to all zeros. Each element $s \in S$ is hashed with every function h_i , and the corresponding bit positions in the filter are set to 1 [SAH24; SBR09]:

$$\forall s \in S, \forall h_i \in H, \quad b[h_i(s)] = 1 \quad (2.2)$$

Since BFs are binary vectors, the similarity between two BFs, b_1 and b_2 , is computed based on the overlapping 1-bits based on their position. The Dice Coefficient is commonly used for this purpose [SAH24], providing a measure of similarity by comparing the overlap of 1-bits in the two binary vectors. This method allows for efficient computation of similarity between BFs, needs to be applied in the context of PPRL.

$$\text{Dice}(b_1, b_2) = \frac{2 \cdot |b_1 \cap b_2|}{|b_1| + |b_2|} \quad (2.3)$$

In PPRL, the set S consists of n-grams generated from the quasi-identifiers λ . This creates a deterministic relationship between the n-grams present and the set bits in the BF. However, due to the finite length of BFs, collisions occur where different n-grams map to the same

bit position. While this can cause incorrect linkages, it also enhances privacy by distorting frequency distributions [SAH24; VCRS20].

Three primary approaches exist for applying BFs to sensitive data. The first approach, Attribute-Level BFs, encodes each attribute, such as first name or last name, into a separate BF, enabling multiple similarity computations. However, Attribute-Level BFs are more vulnerable to frequency-based privacy attacks. The second approach, Cryptographic Long-Term Key Encoding, merges multiple attributes into a single BF, reducing vulnerability to frequency attacks but remaining susceptible to pattern-mining-based attacks. Finally, Record-Level BFs employ a weighted bit sampling technique to minimize frequency information, enhancing privacy protection while maintaining high linkage quality. Each of these approaches balances privacy concerns with the need for accurate and effective record linkage [VCRS20].

Several privacy-enhancing methods have been proposed to mitigate frequency attacks in BFs. These techniques introduce a trade-off between privacy and linkage quality. One such method is balancing, which ensures an equal number of 1-bits across BFs, thereby reducing the likelihood of frequency-based attacks. Another approach is salting, which randomizes bit positions to prevent direct inference from the BFs. Additionally, XOR folding is used to reduce the BF length while maintaining the bit-wise dependencies necessary for effective linkage. These methods aim to strengthen privacy while retaining the accuracy of the linkage process [SAH24; VCRS20].

A major improvement was introduced by Armknecht et al. [AHS23], who proposed a diffusion layer for BF encodings. This method generates Encoded Linkage Data (ELD), where each bit is computed as the XOR sum of multiple BF bits. The indices for XOR computations are randomly chosen and secretly shared among data owners [AHS23].

By applying diffusion, the deterministic relationship between 1-bits in the ELD and the original n-grams is broken, improving privacy while still enabling approximate matching [AHS23].

BFs remain a core technique in PPRL due to their efficiency and scalability. However, their vulnerability to frequency attacks has led to improvements such as Record-Level BFs and diffusion layers, which enhance privacy at the cost of increased computational complexity [AHS23; SAH24; VCRS20].

2.2.2. TMH

TMH is a variation of MinHash initially introduced for efficient estimation of set similarities and later adapted for privacy-preserving probabilistic record linkage. MinHash itself was first proposed in the context of document resemblance and containment estimation. TMH extends MinHash by employing tabulation-based hashing, which enhances its security compared to BFs [Bro97; VCRS20].

MinHash aims to approximate the Jaccard similarity between two sets, S and S' . The fundamental idea is to represent both sets as sequences of randomly ordered elements and apply multiple rounds of random permutations, π and π' , to shuffle them. After each round, the first elements of both sequences are compared. The larger the intersection between S and S' , the higher the probability that the first elements will match. The final Jaccard similarity estimate is computed based on the number of hash collisions achieved during permutation [Bro97; SAH24; VCRS20].

Instead of explicitly computing these permutations, MinHash simulates them by applying a suitable hash function to the elements of a set and selecting the smallest hash value as the representative signature. This is equivalent to sorting set elements by their hash values and

returning the first element [SAH24].

Tabulation-based hashing is a technique used in **TMH** that provides efficient and high-quality hash functions by leveraging precomputed lookup tables. This method operates as follows [VCRS20]:

The process begins with the **initialization** of l sets of lookup tables, each containing c tables. Each table holds randomly generated bit strings for keys of length k , with a key space of 2^k . During the **hashing process**, each element in S is hashed using a one-way hash function, producing a fixed-length binary value. This binary value is then split into c sub-keys, each of length k . Each sub-key is used as an index to retrieve a random bit string from the corresponding lookup table, and the retrieved c bit strings are XORed together to produce a single output bit string. In the **MinHash signature generation** phase, this process is repeated for each of the l lookup table sets, and the minimum value among all generated bit strings is selected as the MinHash signature [SAH24; VCRS20].

To further enhance privacy, **TMH** employs a 1-bit hashing mechanism, where only the least significant bit of each MinHash signature is retained. These l bits are then concatenated to form the final bit array used as an encoded representation [SAH24].

The main advantage of **TMH** over **BFs** is its improved resistance to frequency-based attacks due to the complexity introduced by tabulation-based hashing. However, this security enhancement comes at a cost. It leads to higher computational overhead, as the need to generate and access multiple lookup tables increases processing time. Additionally, there is increased memory consumption because storing large precomputed tables requires additional space. These trade-offs must be considered when choosing between **TMH** and other privacy-preserving techniques [SAH24; VCRS20]. Despite these trade-offs, **TMH** remains an attractive alternative for **PPRL** due to its robustness against adversarial attacks.

Similar to **BFs**, **TMH** encodes each record as a bit vector of length l . Given two **TMH**-encoded bit vectors, their similarity can be estimated using a modified Jaccard coefficient, adapted to account for artificial bit collisions caused by truncation to the least significant bit. The Jaccard coefficient can also be converted into the Dice coefficient for improved comparability with **BF**-based methods [SAH24; VCRS20].

Overall, **TMH** provides a more secure encoding alternative to **BFs** in **PPRL**, though at the expense of increased computational and memory requirements [SAH24; VCRS20].

2.2.3. TSH

TSH is the most recent encoding scheme proposed for **PPRL**, introduced in 2020 [VCRS20]. **TSH** was designed to address both the privacy vulnerabilities of **BFs** and the computational complexity of **TMH** while maintaining accuracy in similarity calculations. Similar to other encoding techniques, **TSH** requires the input to be split into a set of n -grams S prior to encoding [SAH24].

As a result of **TSH** encoding, each record from a sensitive database is represented by a set of integers, which can be directly used to compute Jaccard similarity. **TSH** employs two distinct hashing steps. In the first hashing step, the input set is converted into a bit matrix representation. In the second hashing step, the bit matrix columns are mapped into integers, enabling efficient comparison. This two-step process allows **TSH** to represent sensitive data in a way that facilitates effective similarity computation while preserving privacy [SAH24]. These steps provide accurate Jaccard similarity calculations while improving privacy protection compared to traditional **BF**-based encodings [VCRS20].

In the first step of the **TSH** process, elements of the n -gram set S are hashed into k independent **BFs** b_i of length l , meaning each hash function results in a corresponding bit vector. This generates a $k \times l$ matrix, where each row corresponds to a **BF** created using a unique hash function, and each column represents the bitwise state across all **BFs** for a given position. In the second step, after constructing the bit matrix, **TSH** computes column-wise hashes to convert the bit vectors into integer representations. Each column vector is treated as an input for a hash function, and all-zero columns are skipped to prevent distortion in similarity calculations since they do not encode any n -grams. To enhance security and avoid hash collisions between columns with identical bit patterns, a salt value and the column index are concatenated before hashing [SAH24; VCRS20].

The final integer representation for each column i for $1 \leq i \leq l$ is computed as [SAH24]:

$$H(\text{salt}, i, b_{1i}, b_{2i}, \dots, b_{ki}) \quad (2.4)$$

The output of the second hashing step is a set of integers, allowing similarity computations using the Dice coefficient rather than directly computing bitwise similarity. Since the encoded data consists of sets, Jaccard similarity can also be computed similarly to MinHash-based encodings [SAH24].

To improve efficiency, **TSH** can be implemented using a Pseudo-Random Number Generator (**PRNG**) instead of cryptographic hash functions. The **PRNG** is seeded with the value to be hashed before generating random numbers, ensuring that the sequence of generated values depends deterministically on the input [SAH24].

By combining efficient bit vector representations with integer-based similarity computations, **TSH** offers a balance between privacy, security, and computational efficiency, making it a promising alternative to existing **PPRL** encoding schemes [SAH24; VCRS20].

2.3. GMAs

GMAs were first introduced by Vidanage et al. [VCRS20] and represent the most significant threat to **PPRL** due to their universal applicability. Unlike traditional cryptanalytic attacks, **GMAs** exploit the fundamental properties of non-interactive **PPRL** to compromise the security of all schemes relying on similarity-preserving encoding [SAH24].

Non-interactive **PPRL** refers to linkage schemes where data owners independently encode their data and share it with a linkage unit. The linkage unit then performs record matching solely based on the encoded data, without requiring further interaction with the data owners during the linkage process. This approach minimizes communication overhead and computational complexity, as no iterative exchanges between parties are necessary. In contrast, interactive **PPRL** methods involve multiple rounds of communication between data owners and the linkage unit to refine matching results or improve accuracy [kum2014privacy].

In **PPRL**, encoded records are linked based on similarity computations. Since these similarities serve as identifiers, an attacker with access to both encoded and plaintext data can leverage them to re-identify individuals. The latest version of the **GMA** developed by Schaefer et al. overcomes the limitations of the original attack by Vidanage et al. and enhances success rate and robustness, even under limited knowledge scenarios [SAH24].

In the context of a **PPRL** system, the attacker is modeled as the linkage unit and is assumed to have minimal prior knowledge. The attacker does not know any encoding secrets, seeds, or salts used in the system to protect the data. The only information available to the attacker is

that which is inevitably known to the linkage unit during the linkage process. This assumption ensures that the attacker can only exploit data accessible through normal system operations, adhering to Kerckhoffs’s principle [SAH24].

Since the attack does not depend on specific encoding parameters or attribute frequency distributions, it is universally applicable as long as pairwise similarities of encoded data are available [SAH24].

The first step of the attack involves constructing similarity graphs for both the encoded dataset (D_{enc}) and the plaintext dataset (D_{plain}). In these graphs, each node represents an individual record, while edges between nodes are assigned weights based on pairwise similarity computations. To ensure computational efficiency and focus only on meaningful connections, edges with similarity scores below a predefined threshold are omitted, reducing noise and improving the accuracy of the attack [SAH24].

Since certain encoding properties, such as BF length (l), are inevitably known to the linkage unit, D_{plain} can be transformed analogously to D_{enc} for effective comparison. Importantly, this step does not require knowledge of shared secrets, as the primary objective is to replicate the effect of encoding on similarity [SAH24].

To quantify the structural similarity between nodes in G_{plain} and G_{enc} , node embeddings are computed to transform the graph structure into a numerical representation. This process begins with graph embedding using the Node2Vec algorithm, which applies a Word2Vec-like approach to learn vector representations of nodes. During this process, nodes undergo multiple random walks, where each walk simulates a sequence of transitions between connected nodes. These sequences are then treated as sentences, allowing the model to learn embeddings that capture the local and global structure of the graph. The behavior of these random walks is controlled by two hyperparameters: p , which determines the likelihood of returning to a previously visited node, and q , which influences the tendency to explore new regions of the graph. The result is an embedding matrix where each row represents a node as a vector in Euclidean space [SAH24].

Once embeddings are generated, they must be aligned to allow meaningful comparison between the two graphs. Due to the randomness inherent in embedding generation, direct comparison is not possible. Instead, an iterative approach is used to solve two subproblems: first, an optimal linear transformation is determined using Procrustes Analysis to align the embeddings, and second, node correspondences are established via the Sinkhorn Algorithm, which minimizes the Wasserstein distance between the distributions of embeddings in both graphs. To achieve an effective alignment, an unsupervised stochastic optimization scheme alternates between these two steps over n epochs, gradually refining the transformation and correspondences until convergence [SAH24].

Once the embeddings from the plaintext and encoded datasets are aligned, the reidentification process can begin. Each embedding in the transformed plaintext space is compared to its counterparts in the encoded space, with similarity measured using cosine similarity. This metric quantifies how closely two embeddings align in the high-dimensional space, enabling the attacker to identify records in the encoded dataset that most closely resemble those in the plaintext dataset [SAH24].

The final step involves constructing a bipartite graph, where nodes from the plaintext and encoded datasets are linked based on their similarity scores. To determine the optimal mapping, the Jonker-Volgenant algorithm is applied, ensuring that each node in the smaller dataset is uniquely matched to a corresponding node in the larger dataset. This algorithm maximizes the total similarity across all matched pairs, effectively revealing the identities of individuals

within the encoded dataset [SAH24].

The novel **GMA** approach by Schaefer et al. achieves near-perfect re-identification rates when dataset overlap is 100%. Even for low-overlap scenarios (e.g., 5%), success rates reach 99.9% for **TSH** [SAH24]. The only encoding scheme resistant to **GMA**s is **BF**s with diffusion layers, which disrupts similarity preservation for sufficiently high diffusion values [SAH24].

2.4. **ANNs**

3. Methodology

3.1. Modifications to the GMA

3.2. Design and Implementation of the DEA

3.2.1. Problem Definition

3.3. Data Representation

3.3.1. ANN Architecture for DEA

3.3.2. Training the Model

4. Results

4.1. Evaluation Metrics

4.2. Experiments

4.3. Analysis

4.4. Discussion

5. Conclusion

5.1. Summary

5.2. Future Work

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A. Auxiliary Information

Eidesstattliche Erklärung

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DATUM

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